High Resolution Measurements of Supersonic Shear Flow Mixing and Combustion

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Annual Progress Report

AFOSR Grant No. F49620-98-1-0003

Department of Aerospace Engineering
The University of Michigan
Ann Arbor, MI 48109-2140

August 1998

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE ~~September 1, 1998~~	3. REPORT TYPE AND DATES COVERED Annual Technical Report

4. TITLE AND SUBTITLE
(U) High Resolution Measurements of Supersonic Shear Flow Mixing and Combustion

5. FUNDING NUMBERS
PE – 61102F
PR – 2308
SA – BS
G – F49620-98-1-0003

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION(S) AND ADDRESS(ES)
Department of Aerospace Engineering
The University of Michigan
Ann Arbor, MI 48109-2140

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING ORGANIZATION NAME(S) AND ADDRESS(ES)
AFOSR/NA
110 Duncan Avenue, Suite B115
Bolling AFB, DC 20332-0001

10. SPONSORING ORGANIZATION REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum: 200 words)*

An initial experimental study of the effects of compressibility on the outer variable scalings and large-scale structure of a supersonic coflowing turbulent jet operating in the wake-like mode was completed. The results showed that the large-scale structure is clearly evident in the downstream portion of the flow, where the convective Mach number has become subsonic. However the structures appear to be suppressed in the upstream portion of the flow, at supersonic convective Mach numbers. The results also showed that the local flow width and growth rate in the downstream portions of the flow are good in agreement with the scaling laws forthe corresponding incompressible flow.

14. SUBJECT TERMS
Supersonic Mixing; Supersonic Combustion; Turbulent Combustion; Flames

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

Standard Form 298 (890104 Draft)
Prescribed by ANSI Std. 239-18
298-01

HIGH RESOLUTION MEASUREMENTS OF SUPERSONIC SHEAR FLOW MIXING AND COMBUSTION

AFOSR Grant No. F49620-98-1-0003

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Summary/Overview

Achieving supersonic mixing and combustion while maintaining acceptable flame stability characteristics and emissions of trace chemical species are key to the development of improved airbreathing propulsion systems. The present investigation contributes to this objective by making high-resolution imaging measurements of the physical structure of supersonic mixing and combustion in a turbulent shear flow. The work consists of two major parts.

The first part is an experimental and theoretical investigation of the outer-scale properties of mixing and combustion in a supersonic shear flow facility. Emphasis is on measuring changes in the large-scale structure and growth rate of a two-dimensional supersonic turbulent shear flow due to compressibility effects, and comparing with results obtained in supersonic mixing layers elsewhere in the AFOSR program. Comparisons with results from mixing layers allow identification of the effects of compressibility that are generic to all supersonic turbulent shear flows. This work also builds on recent advances in understanding density effects due to heat release on the growth rates and other outer-scale properties of turbulent shear flows. Density effects due to compressibility are being analyzed similarly to develop fundamental understanding and predictive modeling capabilities for supersonic turbulent shear flows.

The second major part of this work is investigating the fully-resolved four-dimensional spatio-temporal structure of the fine scales of molecular mixing in subsonic and supersonic turbulent shear flows. A recently-developed measurement system will permit the first-ever simultaneous study of the combined four-dimensional spatial and temporal structure of the conserved scalar field $\zeta(\mathbf{x},t)$, the molecular mixing rate field $\nabla\zeta\cdot\nabla\zeta(\mathbf{x},t)$, and the underlying vorticity and strain rate fields $\omega_i(\mathbf{x},t)$ and $\varepsilon_{ij}(\mathbf{x},t)$ in a gaseous turbulent shear flow. These measurements will permit essential new insights to be gained into the fundamental issues that dominate the coupling between turbulent flow, molecular mixing, and nonequilibrium reaction chemistry in turbulent combustion systems.

Technical Discussion

During the past year we have obtained extensive experimental results for the outer-scale properties and large-scale structure of supersonic turbulent jets operating in the wake mode. Typical results are shown in Figs. 1 and 2. There are indications that the large-scale structure of the flow, which is clearly evident in the further downstream parts of the flow, where the local Mach number is become subsonic, may be suppressed in the upstream portion of the flow. This is being further investigated. However, the local flow width $\delta(x)$ and growth rate $d\delta/dx$ in Figs. 2 and 3 show results consistent with the $(x/\vartheta)^{1/2}$ scaling that is characteristic of the corresponding subsonic flow, even in the upstream parts of the flow. This can be clearly seen in the log-log plots in Fig. 3, where it can be further observed that this conclusion appears to be independent of the choice of flow width definitions.

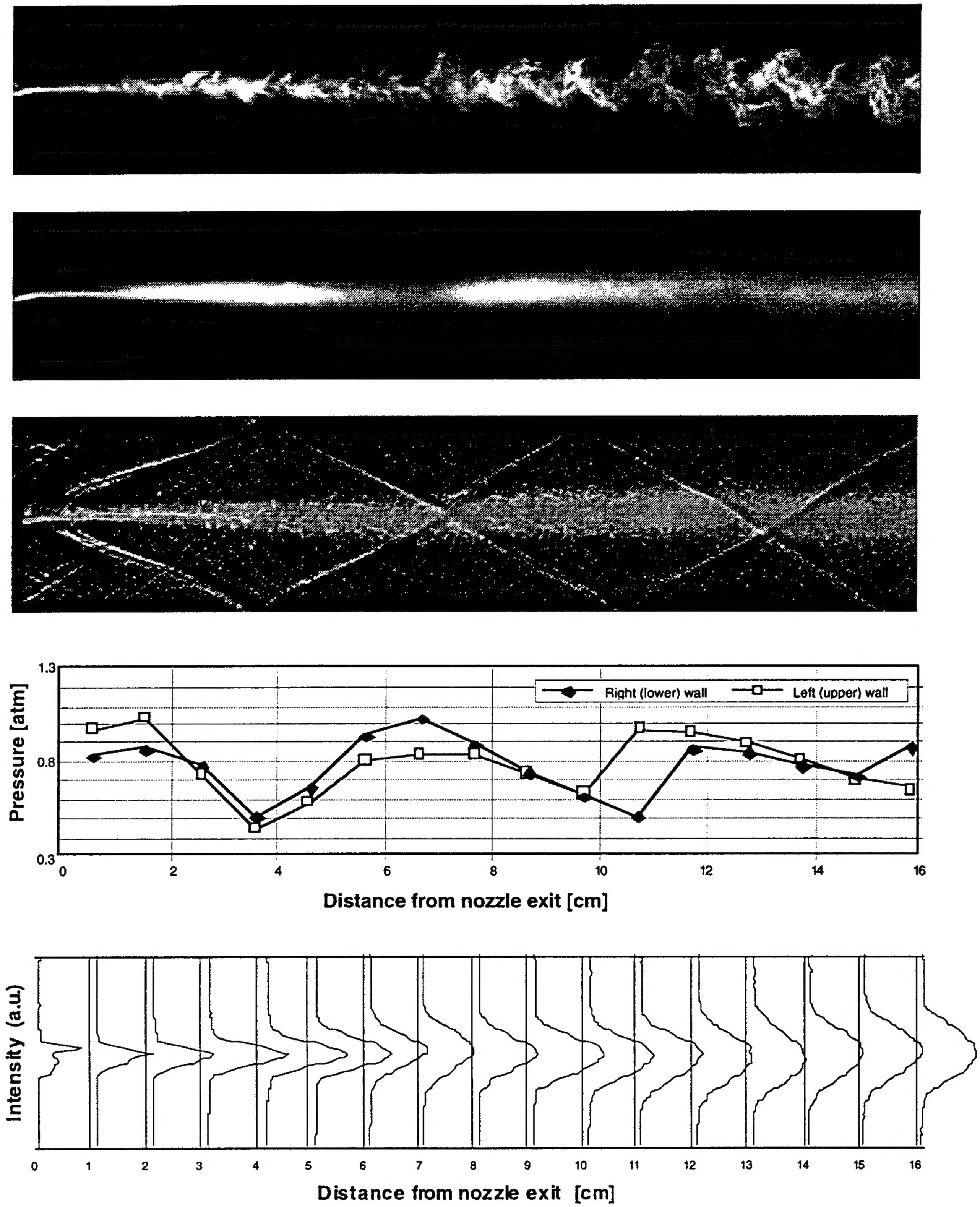

Fig. 1. Typical experimental results for outer-scale properties obtained in the two-dimensional supersonic turbulent shear flow, showing instantaneous mixing regions and large-scale structure as visualized by alcohol fog technique *(top)*, ensemble average *(second)*, with supersonic wave structure superimposed *(third)*, wall static pressure measurements *(fourth)*, and local flow width d(x) as indicated from second panel. See also Fig. 2. Growth rates obtained from bottom panel are shown in Fig. 3.

Several supersonic hydrogen-air flames were imaged in our Supersonic Mixing and Combustion Facility. Acetone PLIF was used to visualize the fuel concentrations in the jet-like flames, and OH PLIF was used to visualize the reaction zones. The supersonic flames that were studied were partially lifted, having a flame base that is stabilized in a recirculation zone behind the bluff-body fuel injector. It was found that the structure of the supersonic flames is closer to that of a partially premixed flame, and is very different from the structure of a conventional attached subsonic jet flame.

The partial premixing of hydrogen and air is enhanced by the extremely strong recirculation zone downstream of the fuel injector, which is driven by the Mach 2.5 airstream. The OH reaction zone structure has the appearance of a tangled web of thin reaction layers for subsonic coflow air; as the coflow air becomes supersonic the layers become thicker and merge, and the instantaneous OH concentrations become spatially diffuse. The increased homogeneity of the OH reaction zone at supersonic conditions is attributed to the intense premixing of fuel and air prior to combustion. Our experimental observations provide strong evidence that the flame is partially premixed, which emphasizes the need to develop new models, especially those that can represent a complex set of reaction layers, some of which are diffusion layers and some partially premixed flames.

We have also initiated an ongoing interaction with researchers at the Air Force's WPAFB in Dayton, OH (T. Jackson, J. Donbar). The first phase of this interaction has been completed; Michigan Ph.D. candidates operated advanced PIV / OH / CH diagnostics at WPAFB to answer fundamental research questions relating to turbulent mixing and reaction. For the first time, the CH and OH reaction zone structure and the hydrodynamic strain rate were measured in an intensely turbulent nonpremixed flame. A regime of combustion was investigated in which the intense turbulence and long residence times provided extremely large degrees of flame wrinkledness and large values of flame surface density. Some partial premixing was observed in certain cases. The relevant nondimensional parameters that characterize this regime of combustion are being deduced from the data.

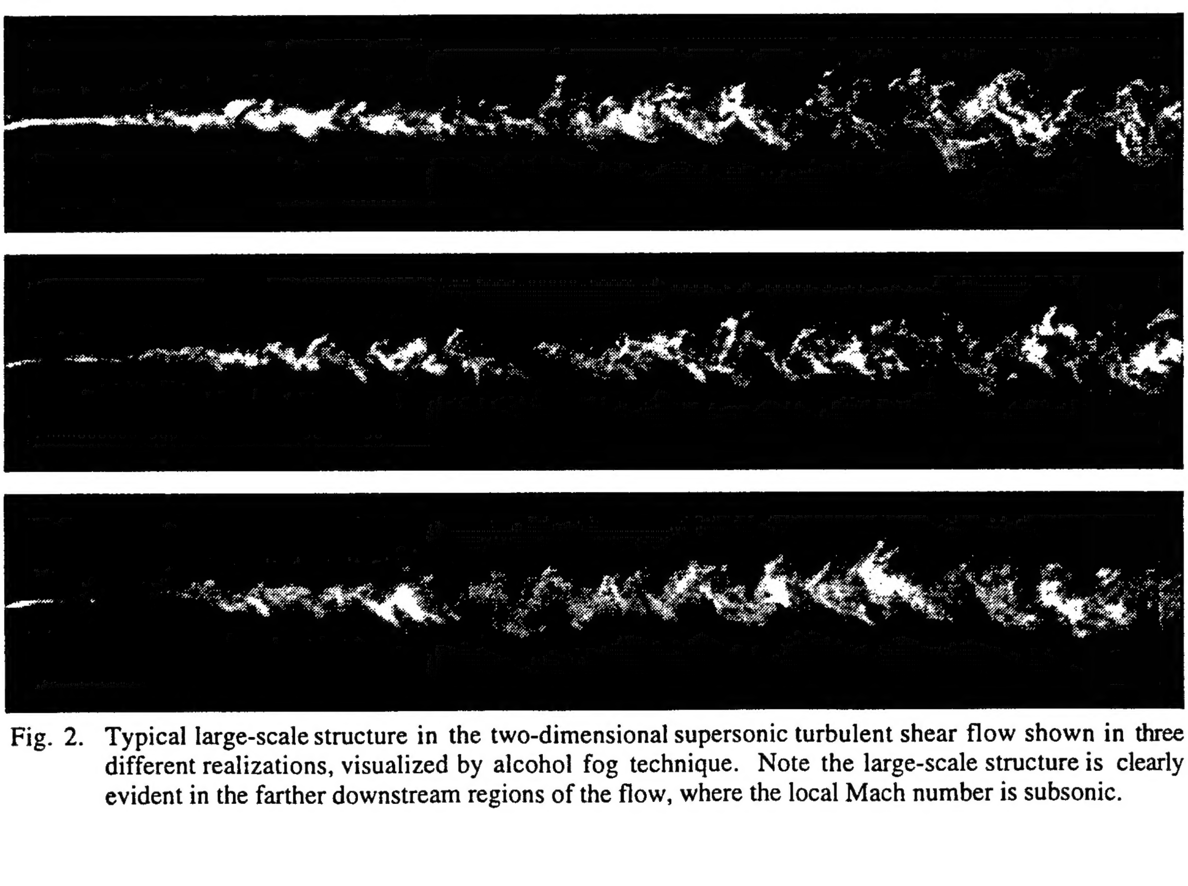

Fig. 2. Typical large-scale structure in the two-dimensional supersonic turbulent shear flow shown in three different realizations, visualized by alcohol fog technique. Note the large-scale structure is clearly evident in the farther downstream regions of the flow, where the local Mach number is subsonic.

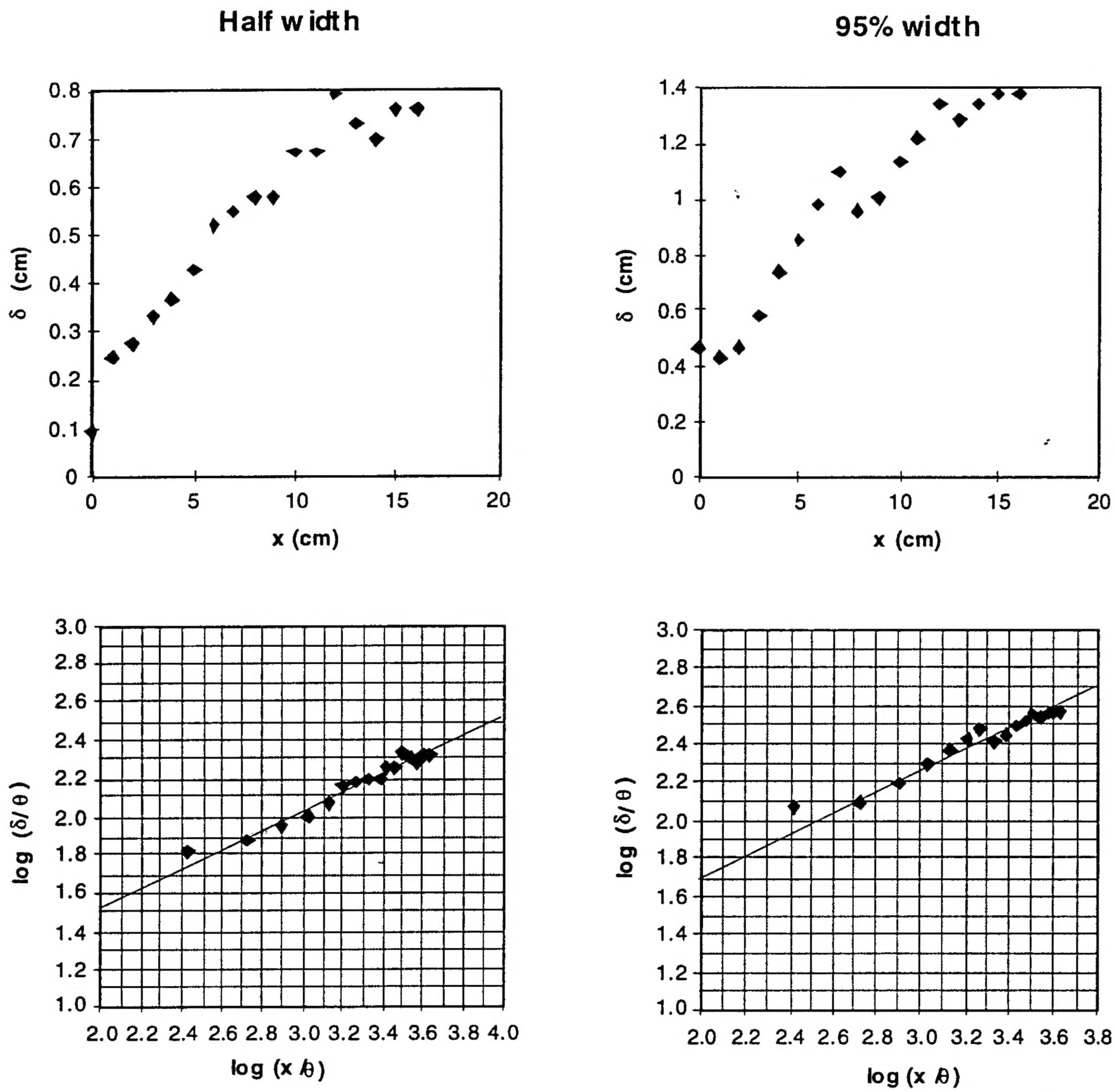

Fig. 3. Measured variation in local outer-scale flow width $\delta(x)$ defined by half-width *(left)* and 95% width *(right)* with downstream distance x/ϑ in the two-dimensional supersonic shear flow, shown in linear form *(top)* and logarithmix form *(bottom)*. Note straight line gives $(x/\vartheta)^{1/2}$ power law scaling.

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Principal Investigator Annual Data Collection (PIADC) Survey Form

PI DATA

Name (Last, First, MI)	DAHM, Werner J.A.	AFOSR USE ONLY	
Institution	The University of Michigan	Project/Subarea:	/
Contract/Grant No.	F49620-98-1-0003	NX	
		FY	

NUMBER OF CONTRACT/GRANT CO-INVESTIGATORS

Faculty 1   Post Doctorates 0   Graduate Students 1   Other 0

PUBLICATIONS RELATED TO AFOREMENTIONED CONTRACT/GRANT

Name of Journal, Book, etc: Physics of Fluids

Title of Article: Experimental assessment of Taylor's hypothesis and its applicability to dissipation estimates in turbulent flows

Author(s): Dahm, W.J.A. & Southerland, K.B.

Publisher (if applicable): American Institute of Physics

Volume: 9   Page(s): 2101-2107   Mo. Publ.: ____   Yr. Publ.: 1997

Name of Journal, Book, etc: Journal of Fluid Mechanics

Title of Article: Experimental assessment of fractal scale similarity in turbulent flows. Part 2: Higher dimensional intersections and nonfractal inclusions

Author(s): Frederiksen, R.D., Dahm, W.J.A. & Dowling, D.R.

Publisher (if applicable): Cambridge Univ. Press

Volume: 338   Page(s): 89-126   Mo. Publ.: ____   Yr. Publ.: 1997

Name of Journal, Book, etc: Journal of Fluid Mechanics

Title of Article: Experimental assessment of fractal scale similarity in turbulent flows. Part 3: Multifractal scaling

Author(s): Frederiksen, R.D., Dahm, W.J.A. & Dowling, D.R.

Publisher (if applicable): Cambridge Univ. Press

Volume: 338 Page(s): 127-155 Mo. Publ.: ______ Yr. Publ.: 1997

Name of Journal, Book, etc: Journal of Fluid Mechanics

Title of Article: Experimental assessment of fractal scale similarity in turbulent flows. Part 4: Effects of Reynolds and Schmidt numbers

Author(s): Frederiksen, R.D., Dahm, W.J.A. & Dowling, D.R.

Publisher (if applicable): Cambridge Univ. Press

Volume: to appear Page(s): ______ Mo. Publ.: ______ Yr. Publ.: 1998

Name of Journal, Book, etc: Journal of Fluid Mechanics

Title of Article: Experimental study of the fine-scale structure of conserved scalar mixing in turbulent flows. Part II. $Sc \approx 1$

Author(s): Buch, K.A. & Dahm, W.J.A.

Publisher (if applicable): Cambridge Univ. Press

Volume: 364 Page(s): 1-29 Mo. Publ.: ______ Yr. Publ.: 1998

Name of Journal, Book, etc: Proceedings of the 13th U.S. National Congress of Applied Mechanics

Title of Article: Global scalar field measurements and whole-field scalar imaging velocimetry in turbulent flows

Author(s): Dahm, W.J.A. & Tacina, K.M.

Publisher (if applicable): ______

Volume: ______ Page(s): ______ Mo. Publ.: ______ Yr. Publ.: 1998

HONORS/AWARDS RECEIVED DURING CONTRACT/GRANT LIFETIME

Honor/Award: ______ Year Received: ______

Honor/Award Recipient: ______

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Honor/Award: ______________________________ Year Received: __________

Honor/Award Recipient: ______________________________

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TECHNOLOGY TRANSITIONS

Result: d+ method for heat release effects on mixing

Customer: Energy Systems Associates (ESA)

Contact: Dr. Ben Breen, ESA (Pittsburgh, PA) (412) 429-3259

Application: Development of FLGR system at Duke Power Company's Riverbend Unit 7

Result: d+ method for heat release effects on mixing

Customer: Fuel Tech Inc.

Contact: Dr. Roy Johnson, Fuel Tech Inc. (Naperville, IL) (630) 983-3242

Application: Development of amine-enhanced FLGR system at PSE&G Mercer Unit 22

Result: d+ method for heat release effects on mixing

Customer: Praxair, Inc.

Contact: Dr. Sho Kobayashi, Praxair, Inc. (Tarrytown, NY) (914) 345-6470

Application: Development of DOC system Auburn steel reheat furnace